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Soil greenhouse gas emissions from afforested organic soil croplands and cutaway peatlands

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The effects of land-use and land-use change on soil greenhouse gas (GHG) fluxes are of concern due to Kyoto Protocol requirements. To quantify the soil GHG-fluxes of afforested organic soils in Finland, chamber measurements of soil CO_2, CH_4 and N_2O fluxes were made during the years 2002 to 2005 on twelve organic soil cropland and six cutaway peatland sites afforested 9 to 35 years ago. The annual soil CO_2 effluxes were statistically modelled using soil temperature as the driving variable and the annual CH_4 and N_2O fluxes were estimated using the average fluxes during the measurement period. Soil CO_2 effluxes on afforested organic soil croplands varied from 207 to 539 g CO_2-C m^{-2} a^{-1} and on cutaway peatlands from 276 to 479 g CO_2-C m^{-2} a^{-1}. Both the afforested organic soil cropland and cutaway peatland sites acted mainly as small sinks for CH_4; the annual flux ranged from –0.32 to 0.61 g CH_4-C m^{-2}. Afforested organic croplands emitted more N_2O (from 0.1 to over 3.0 g N_2O-N m^{-2} a^{-1}) than cutaway peatland sites (from 0.01 to 0.48 g N_2O-N m^{-2} a^{-1}). Due to the decrease in soil CO_2 efflux, and no change in CH_4 and N_2O fluxes, afforestation of organic croplands appears to decrease the greenhouse impact of these lands.

Introduction

There is increasing evidence that the Earth's climate is changing because of the rising concentration of greenhouse gases (GHG) in the atmosphere. Sequestration of carbon (C) has been recognised as an important environmental impact of afforestation. Under Article 3.3 of

the Kyoto Protocol (UN 1997), GHG removals and emissions due to afforestation, reforestation and deforestation since 1990 are accounted for in meeting the Protocol's emission targets. In the IPCC methodology, afforestation of organic soil croplands and cutaway peatlands can be seen as a possible means of offsetting national GHG emissions in addition to other activities related to land-use, land-use change and forestry (LULUCF) (Sampson and Scholes 2000). The most evident effect of afforestation is the sequestration of atmospheric CO_2-C into the growing tree biomass. Changes in soil GHG fluxes are more difficult to predict. Documentation of the GHG-fluxes after afforestation is part of the national GHG inventory process (GPG-LULUCF; Penman *et al*. 2003). The IPCC GPG encourages countries to use or collect nationally specific information in order to better reflect national circumstances and reduce uncertainty.

The area of cultivated organic soils (organic matter (OM) content > 20%) in Finland has decreased from the almost one million hectares drained for agricultural use to the present 300 000 ha (Myllys and Sinkkonen 2004). From the total area of 1 200 000 ha of peatlands suitable for peat production in Finland (Virtanen and Hänninen 2004), annual peat harvesting area has been 42 000–59 000 ha during the last ten years. Peat harvesting has already ceased on more than 20 000 ha and by 2010 this area will have increased to 40 000–45 000 ha (Selin 1999).

Large-scale afforestation of agricultural land, aimed at reducing the area under cultivation in the country, began in the late 1960s. Of the over 240 000 ha of afforested agricultural land (Finnish Statistical Yearbook of Forestry 2004) the area on peat soils is estimated to be more than 80 000 ha (Wall and Heiskanen 1998). Forestry is also considered to be the main after-use option for cutaway peatlands (Selin 1999). The most common tree species planted on former agricultural lands and cutaway peatlands have been Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), and silver birch (*Betula pendula*) (Aro *et al*. 1997, Hynönen and Hytönen 1998).

During agricultural use or fuel peat production peatlands are efficiently drained. Peat production practices and continuous cultivation measures such as ploughing and harrowing, fertilization, liming and addition of mineral soil change the physical, chemical and biological properties of the peat soil (Wall and Hytönen 1996, Aro *et al*. 1997, Hytönen and Wall 1997). In the case of both cutaway peatland and cropland soils the peat is generally well humified, and it has a high bulk density and high nitrogen content. Converting peatlands to agricultural use or for peat harvesting enhances peat decomposition and turns the peatland from a CO_2 sink into a source (Nykänen *et al*. 1995, 1996, Tuittila *et al*. 1999, Maljanen *et al*. 2001a, 2004, Lohila *et al*. 2004). Due to the increased depth of the aerobic surface peat layer after drainage, these areas may be transformed into minor sinks of atmospheric CH_4 (Maljanen *et al*. 2003b). In general, agricultural soils are responsible for most of the global nitrous oxide (N_2O) emissions (Kroeze *et al*. 1999), and despite the small area of organic agricultural soils, these soils are estimated to be responsible for 25% of the total anthropogenic N_2O emissions in Finland (Kasimir-Klemedtsson *et al*. 1997).

Since croplands and cutaway peat soils produce high GHG emissions, various approaches have been considered in order to reduce these emissions. Only scattered data on the effects of afforestation on the soil GHG fluxes from organic soils exist (Maljanen *et al*. 2001b, von Arnold 2005). After afforestation, gradual changes in the soil structure and biology may change the peat decomposition rate. Though the soil respiration rate is mainly regulated by soil temperature and moisture (Lloyd and Taylor 1994, Davidson *et al*. 1998), also substrate properties can have substantial impacts on microbial activity in peat (e.g. Karsisto 1979). Afforestation implies that the annual cycle of cultivating and harvesting agricultural crops is replaced by a much longer forest tree rotation with larger biomass. After afforestation, repeated soil amelioration measures such as tillage, fertilization and liming cease. These factors may change the soil properties to be less favorable for the microbes and thereby lead to a slower decomposition rate of the organic matter and to reduced CO_2 and N_2O emissions. The gradual degradation of the ditch network and consequent decreased aeration of the soil after afforestation may lead to increased CH_4 emissions.

The aim of this study was to produce estimates of the annual soil CO_2, CH_4 and N_2O emissions from typical afforested organic soil croplands and cutaway peatlands in Finland. The specific objectives of this study were (1) to quantify the annual soil GHG fluxes on afforested organic soil cropland and afforested cutaway peatland ecosystems and (2) to describe both the spatial and temporal variation in GHG fluxes caused by edaphic and climatic factors. The results of this study will be utilized in determining the dynamic GHG emission factors of these land use categories (Alm *et al*. 2007).

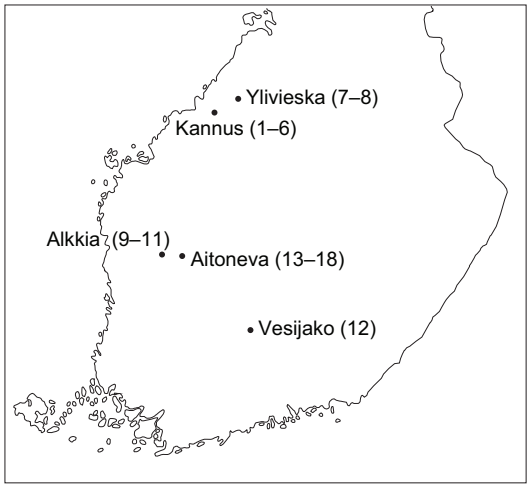

Fig. 1. The locations and site numbers of the study sites.

Material and methods

Experimental sites

Twelve afforested organic soil croplands (AC) (sites 1–12) were selected from four different locations in southern and central Finland (Fig. 1). These sites represented different stand ages, tree species, soil characteristics and peat thicknesses (Tables 1 and 2). All sites had been in agricultural use for some decades before afforestation. During the agricultural phase mineral soil had been added to some of the sites and all sites had been continuously fertilized and limed in order to improve the soil properties for cultivation. After the cultivation practices ceased, the soil was prepared and the sites were afforested.

Afforested cutaway peatlands (ACP) (sites 13–18) were located in the peat production area of Aitoneva, in Kihniö, central Finland (Fig. 1). Aitoneva provides a unique opportunity to study the influence of afforestation on sites with the same land use history but with varying peat thickness, stand age and tree species. The ACP sites were situated no more than one kilometre apart from each other. Six sites were selected to represent different tree species, developmental stages and soil characteristics (Table 2). On all of the sites peat harvesting ceased 15–20 years before afforestation. The mineral soil on the sites 13, 15 and 18 had been mixed into the peat during soil preparation. All the sites had been fertilized with potassium and phosphorus after afforestation.

Afforestation on the sites had been done using either seedlings of Scots pine (*Pinus sylvestris*), silver birch (*Betula pendula*), downy birch (*Betula pubescens*) or alder (*Alnus glutinosa*) or they were naturally regenerated 5–35 years before the measurements began (Table 2).

The thickness of the organic peat layer in the study sites varied considerably (Table 2). The ash content of the 0–20 cm layer determined as loss-on-ignition (550 °C, 8 h) varied from 6% to 82%. The highest ash contents were measured on AC sites and ACP sites having 150 cm and 55 cm of peat, respectively. The C/N ratios (LECO CHN-1000, LECO CHN-2000) were lower on the northern AC sites (1–8) than on the sites located more to the south (sites 9–18) (Table 2).

The temperature sum and mean summer temperature during the study years were higher than the long-term average. There were considerable differences in temperature between the study sites (Table 1). The average water table level (Fig. 2) was fairly low during the dry summer of 2003 and much higher during the summer of 2004.

Measurements and calculations

Soil CO_2 efflux

Field measurements

On each study site, 2–8 sample plots (Table 2) for bare soil CO_2 efflux measurements were

Table 1. The climatic characteristic of the study areas.

Study site[1)]	Site name[1)]	Temperature sum (d.d. °C[2)])				Air temperature (°C)								
						Summer[3)]					Mean annual			
		2002	2003	2004	LT[4)]	2002	2003	2004	MP[5)]	LT[4)]	2002	2003	2004	LT[4)]
1–8	Kannus, Ylivieska	–	1183	1095	1070	–	10.78	10.30	10.60	10.09	–	3.19	3.24	2.18
9–11, 13–18	Alkkia, Aitoneva	1379	1238	1166	1122	11.20	11.07	10.81	11.05	10.49	3.81	3.74	4.16	3.05
12	Vesijako	1470	1325	–	1236	11.75	11.60	–	–	11.18	4.27	4.14	–	3.61

[1)] For location *see* Fig. 1; [2)] Threshold value +5 °C; [3)] Summer = 1 May–31 October; [4)] LT = Long-term average 1970–1999 (Finnish Meteorological Institute 1991); [5)] MP = Soil CO_2 measurement period (7 June 2003–31 October 2003, 1 May 2004–6 June 2004).

Table 2. Study site characteristics.

Site	Previous land use	Tree species	Age year 2005	Stand volume (m^3 ha^{-1})	Tree height (m)	Peat depth (cm)	Bulk density (kg dm^{-3}) 0–20 cm	Ash content (%) 0–20 cm	C/N ratio 0–20 cm	No. of sample plots	
										CO_2	CH_4/N_2O
1	Cropland	Birch	10	2	2.7	74–92	0.218	24.2	19.3	5	–
2	Cropland	Birch	18	16	6.3	56–89	0.250	26.2	13.0	5	4
3	Cropland	Birch	18	27	6.9	43–65	0.250	31.5	17.9	5	4
4	Cropland	Birch	35	193	14.6	32–40	0.262	27.7	18.4	5	4
5	Cropland	Pine	33	137	10.3	46–55	0.182	6.8	18.7	5	8
6	Cropland	Pine	33	75	9.3	62–75	0.278	32.4	17.4	5	8
7	Cropland	Birch	11	12	5.0	> 200	0.250	21.0	18.8	–	5
8	Cropland	Pine	33	104	9.2	> 200	0.240	40.0	18.0	–	5
9	Cropland	Pine	34	157	12.4	150–156	0.899	82.1	22.2	3	4
10	Cropland	Pine	34	177	12.0	167–174	0.540	63.0	26.0	3	4
11	Cropland	Pine	34	121	11.6	135–151	0.503	62.2	28.2	3	4
12	Cropland	Alder	37	159	21.1	69–81	0.557	70.7	19.3	–	2
13	Cutaway	Birch	39	141	21.9	16–17	0.202	19.6	23.8	2	–
14	Cutaway	Birch	30–40	365	17.8	40–72	0.174	6.0	23.4	4	4
15	Cutaway	Birch	27	86	11.3	55–77	0.570	79.3	23.3	4	3
16	Cutaway	Pine	18	24	4.6	5–60	0.193	15.6	26.5	8	8
17	Cutaway	Pine	43	248	16.0	38–55	0.173	6.4	24.5	4	4
18	Cutaway	Pine	29	163	8.9	41–69	0.623	74.7	23.5	4	3

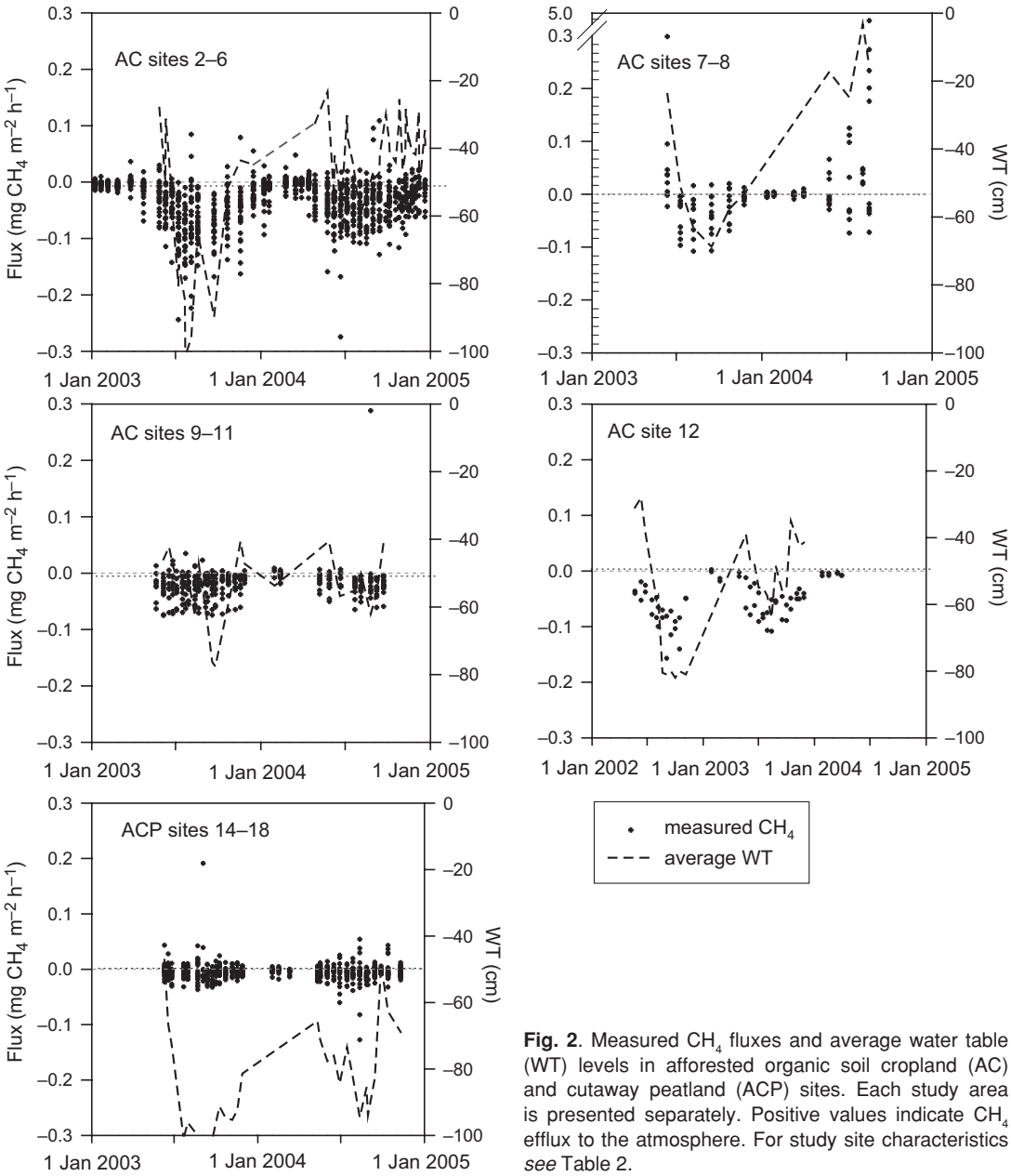

Fig. 2. Measured CH_4 fluxes and average water table (WT) levels in afforested organic soil cropland (AC) and cutaway peatland (ACP) sites. Each study area is presented separately. Positive values indicate CH_4 efflux to the atmosphere. For study site characteristics *see* Table 2.

established in subjectively chosen locations to cover typical variation on the sites, no more than 20 m (AC sites) and 150 m (ACP sites) apart from each other. An aluminum tube with a diameter of 31.5 cm was inserted into the soil to a depth of 30 cm on each sample plot in order to exclude root respiration from the soil CO_2 efflux. The above-ground litter was removed from the sample plots and further accumulation of the fresh litter was prevented by placing a net above the sample plot. To eliminate autotrophic plant respiration, the above-ground parts of the green plants were removed by manual weeding and clipping at the beginning of the measurements. During the measurement period the growing green parts (mainly mosses) were removed when necessary. Depending on the site, measurements lasted for 2 to 3 years from 2002 to 2005 (Fig. 3).

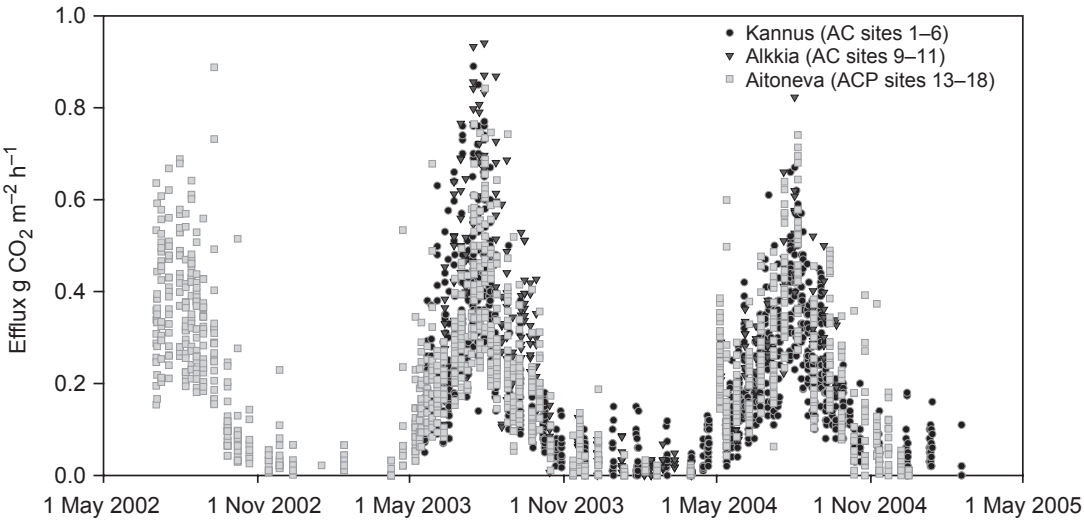

Fig. 3. Measured soil CO_2 effluxes from three different study areas. AC = afforested organic soil cropland, ACP = afforested cutaway peatland.

Measurements were done approximately weekly during the growing season and monthly during the winter (Fig. 3).

The soil CO_2 effluxes were measured using a closed- chamber system with air circulating in a loop between the chamber and an external infrared gas analyser (IRGA) (EGM-4 CO_2 Analyzer, PP-Systems Ltd. UK) equipped with a water vapour equilibrator. An aluminium chamber (height 14.9 cm, basal area 779 cm^2, equipped with a fan) was installed on the sample plot directly over a 2 cm deep groove in the ground. During the period of snow cover, an external collar was used to hold the chamber on top of the snow pack. The CO_2 concentration increase in the chamber was monitored every 4.8 seconds with IRGA for 80 seconds. The soil CO_2 efflux was calculated from the linear increase in the chamber headspace CO_2 concentration with time. The effluxes were corrected for atmospheric pressure and air temperature. Soil temperatures at 5 cm depth were measured in the sample plot simultaneously with the chamber measurements.

Modelling of annual effluxes

Statistical response functions were constructed between measured soil CO_2 fluxes and simultaneously measured soil temperatures at 5 cm depth (T5), separately for each sample plot (coefficients of the individual regression analysis are given in Appendix 1). The relationship between T5 and CO_2 efflux was expressed as an exponential function of the form:

$$R = R_0 e^{kT5} \quad (1)$$

where R_0 and k are fitted parameters. R_0 is the base respiration rate, and k is related to Q_{10}, the factor by which a reaction increases for an increase of 10 °C in temperature. The parameters for the soil efflux functions were calculated by applying non-linear regression using least squares loss function with the Gauss-Newton method (SYSTAT 10 Statistics II). The fits were good except for the lower soil temperatures when the function tended to overestimate the effluxes. Because of this, the measured soil CO_2 efflux data were divided into measurements done during summer (May–October) and those done during winter (November–April).

Soil temperature at 5 cm depth was monitored continuously at all sites. The soil temperature data were collected every 2 to 4 hours using miniature temperature data loggers (i-button, Dallas Semiconductor Corp.). The 2–3 hour gaps were filled by interpolating to obtain hourly soil temperature data. A larger gap on sites 1–6, which lasted from 11 to 18 September 2003, was filled using the data from previous and following weeks.

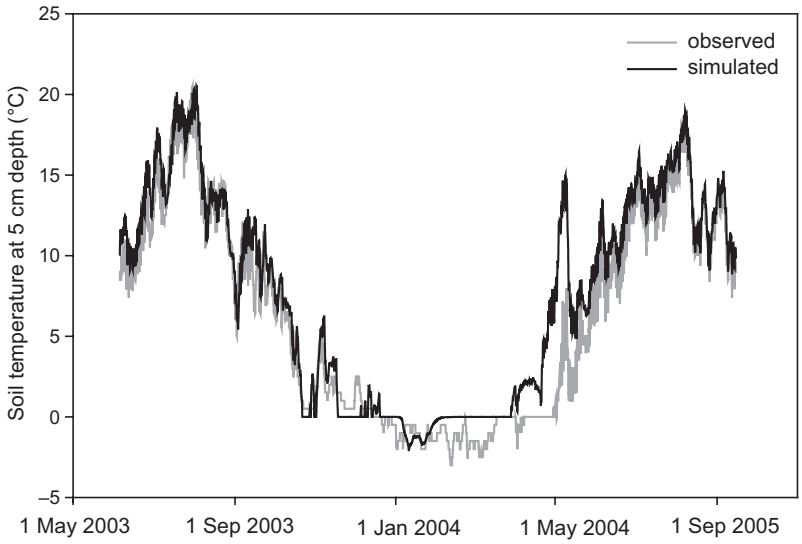

Fig. 4. Simulated and observed soil temperature at Site 6.

Annual soil CO_2 effluxes were calculated for the period 7 June 2003–6 June 2004. Site-specific soil temperature measurements were available for this period for all of the measured sites. Site-specific soil temperature data were used to reconstruct diurnal cycles of soil CO_2 efflux during the summer season by means of regression equations. For the winter season the average effluxes were used.

Simulated weather derived variation in soil CO_2 effluxes

For studying year-to-year variation in soil CO_2 effluxes caused by changes in weather conditions, a 30-year dataset for soil temperature was generated for an AC site at Kannus (Site 6, Table 2). For generating the changing weather conditions we adopted and modified a weather generator originally developed at the University of Joensuu as a part of FINNFOR, a model used to assess the response of boreal forest ecosystem to climate change (Kellomäki *et al*. 1993, Strandman *et al*. 1993). Based on weather data covering the period 1961–1990, a 30-year climatic dataset on air temperature and rainfall with an hourly time step was generated for the location of Kannus. For soil temperature simulations the COUP model (Jansson and Moon 2001) was calibrated for Site 6. Using air temperature and rainfall from the weather simulation program as driving variables, a 30-year soil temperature dataset was simulated. The model calibration results are presented in Fig. 4 in terms of the comparison of simulated soil temperatures at 5 cm depth against the measured data. As compared with the measured soil temperatures, the summer soil temperatures given by the model were overestimated by approximately 15%.

Annual soil CO_2 effluxes during the 30 year time period were calculated separately for each sample plot in Site 6. The summer season's effluxes were calculated using sample-plot-specific response functions (Appendix 1) and modelled hourly 30-year soil temperature data. The average winter effluxes for each sample plot were used for the winter season. As a result of the overestimation of the simulated soil temperature during the summer season, the annual soil CO_2 efflux was overestimated by approximately 10%.

Soil decomposition potential

For studying the site to site variation on soil CO_2 effluxes caused by factors other than soil temperature, the 30-year annual soil CO_2 effluxes were simulated for all sites using the temperature dataset created for Site 6. These average annual effluxes are, hereafter, referred to as the soil decomposition potential. The summer season's effluxes were calculated using sample-plot-spe-

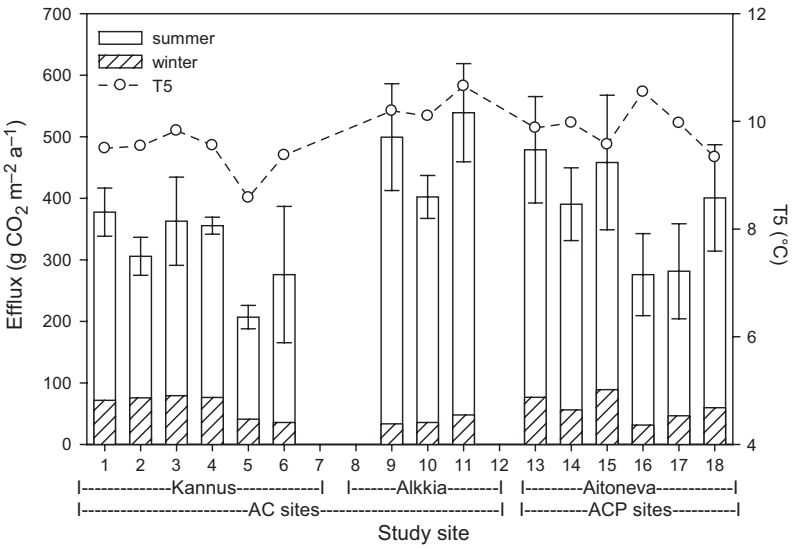

Fig. 5. Average annual soil CO_2 effluxes and standard deviations for the time period 7 June 2003 to 6 June 2004. Summer (May–October) and winter (November–April) fluxes are presented separately. The line depicts the average summertime soil temperature at 5 cm depth. AC = afforested organic soil cropland, ACP = afforested cutaway peatland. For study site characteristics *see* Table 2.

cific response functions (Appendix 1) and the winter season effluxes were interpolated. The relationship between soil CO_2 efflux and peat ash content was tested using simple linear regression.

CH_4 and N_2O measurements

The fluxes of CH_4 and N_2O were measured during the years 2002 to 2005 (Fig. 2) from 2–8 sample plots (Table 2). Square (58 × 58 cm) aluminium collars were used to delimit the permanent sample plots at Kannus, Ylivieska and Alkkia (sites 2–11) and round collars with a diameter of 31.5 cm at Vesijako and Aitoneva (sites 12–18). During the snow-free periods the fluxes of CH_4 and N_2O were measured every 2–3 weeks using the static chamber method (Crill *et al*. 1988) (Fig. 2). Measurements were done using 30 cm high metallic chambers equipped with a fan. The collars had a groove at the upper edge which was filled with water to ensure gas sealing. During the 25 to 35 minute measurement time, four gas samples (10–40 ml) were drawn at fixed intervals from the chamber headspace into polypropylene syringes. On the sites 9–11 and 13–18 the gas samples were stored in glass vials (Exetainer, Labco Inc.) until analysis. The samples were analysed for N_2O and CH_4 using a gas chromatograph equipped with FI- and EC detectors. The fluxes were calculated from the linear gas concentration change in time on the chamber headspace. During the winter, the gas fluxes were studied by measuring the gas concentrations in the snow (Maljanen *et al*. 2003c). Gas fluxes through the snow were calculated using diffusion coefficient (0.139 $cm^{-2}s^{-1}$) for Fick's law as described by Sommerfeld *et al*. 1993 and tested on organic soils by Maljanen *et al*. 2003c.

The median and mean values for summer and winter fluxes for each site were calculated using all available data. Annual flux rates were calculated as the sum of summer and winter season fluxes for each sample plot separately in order to describe the spatial variations within the study sites.

Results

Soil CO_2 efflux

Annual effluxes during measurement period

Annual soil CO_2 effluxes in the studied AC sites (sites 1–6 and 9–11) varied from 207 to 539 g CO_2-C m^{-2} a^{-1} (Fig. 5). The emissions were higher in the south (sites 9–11; mean 480 ± 75 g CO_2-C m^{-2} a^{-1}) than in the north (sites 1–6; mean 314 ± 65 g CO_2-C m^{-2} a^{-1}), where also the summer season mean soil temperature was lower (9.4 °C) than in the south (10.3 °C). The ACP sites (sites 13–18) emitted CO_2 within the range

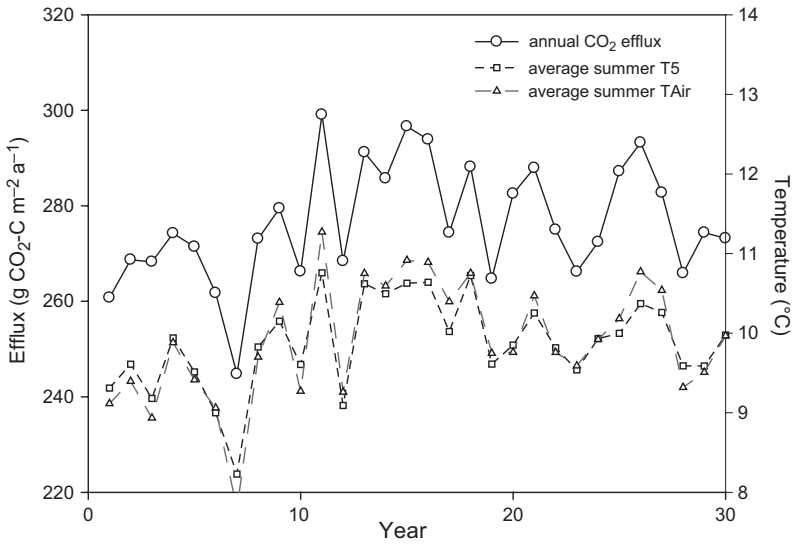

Fig. 6. Simulated annual soil CO_2 effluxes, mean summer air temperature and mean soil temperature at 5 cm depth at afforested organic soil cropland Site 6.

of 275 to 479 g C m^{-2} a^{-1}, the mean being 381 ± 86 g C m^{-2} a^{-1}. During the measurement period the average summertime soil temperature varied between the sites from 8.6 to 10.7 °C. The proportion of the annual efflux emitted during the wintertime on all of the measured sites varied from 9% to 25%, the average being 16%.

Simulated weather-derived variation

Annual soil CO_2 effluxes for a 30 year time span were simulated for site 6 (AC site, Kannus). Over the simulation period the average annual efflux on the site was 276 g CO_2-C m^{-2} a^{-1} (Fig. 6) and when corrected for the 10% overestimation of the simulation process the average efflux is about 250 g CO_2-C m^{-2} a^{-1}. The simulated annual values ranged approximately 10% above and below the long-term average. The average annual effluxes and summer air temperature followed the same pattern. The average summer air temperature explained 88% of the variation of the annual effluxes.

Simulated decomposition potentials between sites

Site-to-site variation of the average annual decomposition potential was studied using the same simulated 30-year soil temperature dataset as the driving variable on all of the sites. In the case of the AC sites the simulated average decomposition potential varied from 227 to 489 g CO_2-C m^{-2} a^{-1} between the sites. The average potential on the AC sites was 357 ± 82 g CO_2-C m^{-2} a^{-1} (Fig. 7). The AC sites in Kannus (sites 1–6) had lower decomposition potentials (316 ± 57 g CO_2-C m^{-2} a^{-1}) as well as lower peat ash contents (25 ± 9%) than on the AC sites in Alkkia, where the decomposition potential was 438 ± 59 g CO_2-C m^{-2} a^{-1} and the peat ash content was 69 ± 11%. Soil CO_2 efflux increased linearly with increasing peat ash content. The peat ash content on the AC sites explained 67% of the variation in peat decomposition potential between the sites. On the ACP sites the decomposition potential varied from 263 to 481 g CO_2-C m^{-2} a^{-1}. The average was slightly higher than on the AC sites (382 ± 88 g CO_2-C m^{-2} a^{-1}). The peat ash content on ACP sites did not explain the site-to-site variation of the decomposition potential (r^2= 0.25) as well as it did on the AC sites.

Methane

Ten of the eleven AC sites were annually small sinks of atmospheric CH_4 (Fig. 8). The annual CH_4 flux varied from –0.32 to 0.61 g CH_4-C m^{-2} a^{-1}. The average was –0.11 ± 0.25 g CH_4-C m^{-2} a^{-1} based on the site mean values

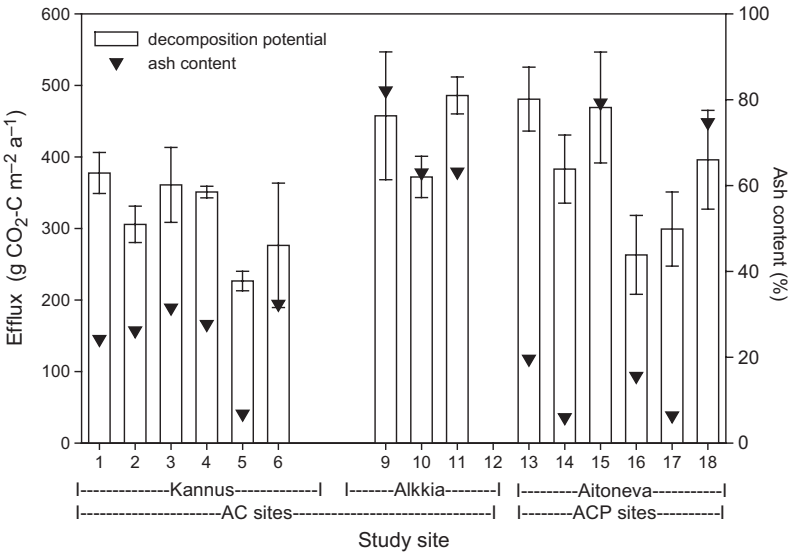

Fig. 7. Peat decomposition potential on the study sites expressed as a three-year simulated annual average of soil CO_2 effluxes. The error bars are standard deviations of the potentials within the study site. The triangles represent the surface peat (0–20 cm) ash contents. AC = afforested organic soil cropland, ACP = afforested cutaway peatland. For study site characteristics *see* Table 2.

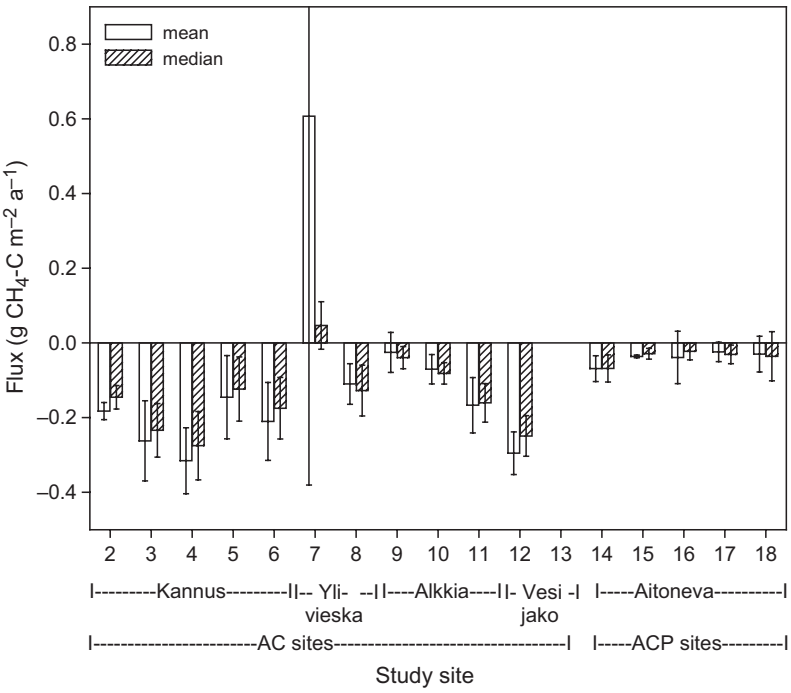

Fig. 8. Annual soil CH_4 fluxes from afforested organic soil cropland and cutaway peatland sites presented as mean and median fluxes. The error bars represent the spatial variation of the fluxes within the study site expressed as standard deviations. AC = afforested organic soil cropland, ACP = afforested cutaway peatland. For study site characteristics *see* Table 2.

and –0.14 ± 0.10 g CH_4-C m^{-2} a^{-1} when based on the median values. The CH_4 fluxes were about the same across the different regions. Site 7 demonstrated some brief periods when the water table level was close to the soil surface and this resulted in rather high CH_4 emissions, which had a powerful impact on the calculated mean annual flux (Fig. 4). The CH_4 uptake on the ACP sites was slightly lower than on the AC sites (Fig. 8). The annual fluxes on the ACP sites varied from –0.07 to –0.02 g CH_4-C m^{-2} a^{-1}. The average was –0.04 ± 0.02 g CH_4-C m^{-2} a^{-1} based on both the mean and median values.

Nitrous oxide

All of the studied sites emitted N_2O. The annual

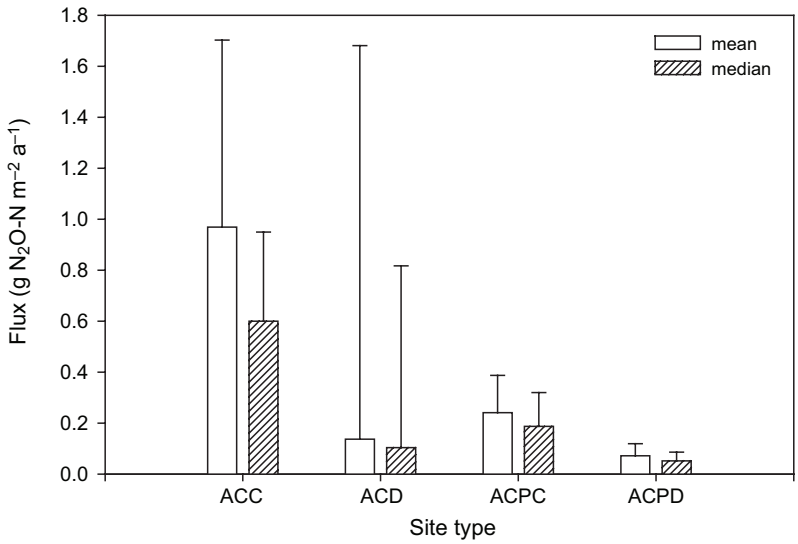

Fig. 9. The annual soil N_2O emissions from afforested organic soil cropland and cutaway peatland sites. The error bars represent the spatial variation of the fluxes between the sites. ACC = afforested organic soil cropland, coniferous species; ACD = afforested organic soil cropland, deciduous species; ACPC = afforested cutaway peatland, coniferous species; ACPD = afforested cutaway peatland, deciduous.

emissions varied greatly between the sites (Fig. 9). Annual N_2O emissions for the AC sites varied from 0.1 to over 3.0 g N_2O-N m^{-2} a^{-1} and were on average 0.95 and 0.35 g N_2O-N m^{-2} a^{-1} for coniferous and deciduous forests, respectively. The nitrous oxide emissions during winter were, on average, 42% of the annual emissions.

The mean N_2O emissions from the ACP sites were lower than those from the AC sites (Fig. 9). The annual N_2O emissions of the ACP sites varied from 0.01 to 0.48 g N_2O-N m^{-2} a^{-1}, the averages being 0.11 and 0.08 g N_2O-N m^{-2} a^{-1} for coniferous and deciduous forests, respectively. The emissions of N_2O during winter were, on average, 22% of the annual emissions.

Tree species, stand age, stand height or volume, depth of peat or water table level were not strictly associated with the annual N_2O emission rates. However, there was a correlation between top soil (0–10 cm) C:N ratios and the annual N_2O emission ($r^2 = 0.58$). The emissions of N_2O decreased exponentially with increasing C/N ratios.

Discussion

Soil CO_2 efflux

The measured soil CO_2 effluxes from the AC sites varied between 207 and 539 g CO_2-C m^{-2} a^{-1}. Since the bare soil CO_2 effluxes from afforested organic soil croplands have not been reported previously, comparisons can only be made with agricultural and forestry-drained peat soils. The soil CO_2 emissions in this study were of the same magnitude as measured by Nykänen *et al*. (1995) on an organic soil grassland in eastern Finland (392–401 g CO_2-C m^{-2} a^{-1}) but much lower than that on organic soil fields in eastern and western Finland as measured by Maljanen *et al*. (2001a) (880–1120 g CO_2-C m^{-2} a^{-1}) and by Maljanen *et al*. (2004) (690–790 g CO_2-C m^{-2} a^{-1}), respectively. Weather conditions, especially summer temperatures, have a strong impact on soil CO_2 efflux. This was demonstrated in this study by the 30-year simulations. During the actual measurement period, the average summer air temperature was 0.5 °C higher than the long-term average summer air temperature (Table 1). Thus the annual soil CO_2 efflux during this measurement period was probably also higher than the long-term average. Measurements on agricultural fields were done in different weather conditions as well as different geographical locations. Comparisons of the measurement periods reveal that the temperature sums were lower during the measurement periods on the agricultural fields than in this study. When this is taken into consideration, the soil CO_2 effluxes after afforestation appear to be lower compared to soils in active agricultural use. Lower effluxes may result because of reduced aeration caused by the cessation of cultivation, the absence of fertilization or

liming activities and lower soil temperatures on the afforested sites caused by the shading effect of the growing tree stand (Londo *et. al*. 1999). All these factors may have led to reduced microbial activity and reduced decomposition rates of organic matter in the soil of the afforested sites when compared to cultivated agricultural soils.

The soil CO_2 emissions on afforested croplands were of the same magnitude or slightly higher than the annual values reported from peatlands drained for forestry by Minkkinen *et al*. (2007a) (248–481 g CO_2-C m^{-2} a^{-1}). Moreover, the instantaneous summer season fluxes on the AC sites (Fig. 3) were somewhat higher than those reported by Silvola *et al*. (1996) (0.2–0.5 g CO_2 m^{-2} h^{-1}). On the studied AC sites the cultivation practices have greatly transformed the peat properties and on almost all of the sites the peat bulk density and ash contents were considerably higher than on peatlands drained for forestry (Kaunisto and Paavilainen 1988, Minkkinen and Laine 1998b). Growing season soil temperatures have been shown to increase linearly with the amount of mineral soil added (Pessi 1956). This may contribute to slightly higher soil CO_2 effluxes on afforested croplands. Mineral soil addition increases the soil pH, as well as the nutrient content (Pessi 1962), and hence accelerates microbial activity and the decomposition rate of organic matter. On afforested organic soil croplands, the amount of mineral soil added to the site is closely related to the surface peat ash content (Wall and Hytönen 1996), which on the studied sites clearly had a positive impact on the peat decomposition potential.

The soil CO_2 emissions on the afforested cutaway sites were clearly higher than the emissions from bare peat surfaces in Aitoneva 20 years after abandonment (seasonal efflux being 52–110 g CO_2-C m^{-2} a^{-1}, Tuittila *et al*. 1999) or from bare *Sphagnum* peat from a peat harvesting area in eastern Finland (annual efflux 240 g CO_2-C m^{-2} a^{-1}, Nykänen *et al*. 1996). In contrast to bare peat surfaces, which had been void of vegetation for several years before CO_2 measurements, the afforested sites in this study have been vegetated for over 20 years before soil respiration measurements. Obviously the growing vegetation has produced fresh carbon as a substrate for heterotrophic microbes, thereby directly increasing the soil respiration rate and also through priming impacts the decomposition rate of old peat. At the beginning of the experiment the present above-ground litter was removed, but undoubtedly some fresh carbon remained in the old peat layer. The observed regrowth of mosses in plots between measurements might imply some autotrophic activity in the soil, indicating that the CO_2 emissions from heterotrophic soil respiration may be overestimated in the present study. All afforested cutaway sites were fertilized in connection with the planting of tree seedlings on the sites. This increase in the peat nutrient content may have accelerated the microbial activity and the decomposition rate of the organic matter compared to non-afforested cutaway peatlands.

The influence of previous land use on soil CO_2 efflux can be studied by comparing the results from the AC sites in Alkkia and the ACP sites in Aitoneva. These two areas are located close to each other within the same climatic region and they were afforested at about the same time. The annual soil CO_2 effluxes on the AC sites were higher (480 g CO_2-C m^{-2} a^{-1}) than those on the ACP sites (381 g CO_2-C m^{-2} a^{-1}). This difference is partly related to the higher soil temperatures measured on the AC sites. However, also the peat decomposition potential (Fig. 7) on the AC sites was higher (440 g CO_2-C m^{-2} a^{-1}) than on the ACP sites (382 g CO_2-C m^{-2} a^{-1}). This may be related to the soil properties, e.g. afforested organic agricultural soils have higher soil pH and higher mineral soil admixture than those on cutaway peatlands. The peat ash content was a bit lower on the ACP sites, but more than this there was not that clear a correlation between the peat decomposition potential and the soil ash content within the AC site data. The texture and nutrient contents of the mineral soil mixed with the peat layer are different in cropland soils and cutaway peatland soils. In the latter, the mineral soil is derived from the sub peat mineral layer by ditching or by soil preparation, and therefore the mineral soil has a lower nutrient content and is probably spatially distributed more heterogeneously than in agricultural peat soils. Thus the measured ash content on the ACP sites may not describe the ash content on the CO_2 sample plots as well as it does on the cropland

sites. Peat decomposition on the ACP sites may be lower also because the development of the microbial populations after peat harvesting may be a slower process than in the AC sites due to the extreme temperature, moisture and nutrient conditions of the ACP sites.

In this study only heterotrophic soil CO_2 efflux was measured. In order to derive the net ecosystem C exchange (NEE), it is necessary to also consider the C input through photosynthesis and C output through leaching. When the C bound by the vegetation (mainly trees) is taken into account, the CO_2 balance of the sites changes considerably. According to eddy covariance measurements, a 30-year-old pine stand growing on an afforested field was only a minor source of atmospheric CO_2 (50 g m^{-2} a^{-1}, Lohila *et al*. 2007). Our results indicate that on afforested cutaway peatlands, assuming a tree growth of 46–329 g CO_2-C m^{-2} a^{-1} (Aro and Kaunisto 2003), the soil CO_2 efflux exceeds the carbon sequestration by tree growth and therefore these areas may act as a source of C into the atmosphere.

Methane

Afforested organic soil cropland sites acted mainly as minor sinks of CH_4 similarly to forestry drained peatlands and peatlands under cultivation (Crill *et al*. 1994, Martikainen *et al*. 1995, Nykänen *et al*. 1995, Maljanen *et al*. 2001b, 2003b, 2004, Minkkinen *et al*. 2007b). Afforestation does not appear to change the soil CH_4 flux on former arable lands provided that the drainage is adequate. Probably the high CH_4 emissions observed on one of the sites (site 7) in August 2004 were caused by the poor drainage of the site leading to anaerobic soil conditions. Since the drainage of afforested organic soil croplands has often been shown to be inadequate (Rossi *et al*. 1993, Hynönen 1997, Hynönen and Saksa 1997, Hytönen 1999) and the soil physical properties are generally rather unfavourable for adequate soil aeration (Wall and Heiskanen 1998) the risk of CH_4 emissions without ditch network maintenance after afforestation is likely. Unlike CO_2 emissions, CH_4 fluxes did not differ between different climatic regions, which indicates that CH_4 fluxes depend especially on the drainage conditions of the site.

The AC sites showed a slightly higher potential to serve as a sink of CH_4 compared to the ACP sites. This may be due to severe growth conditions (i.e. large fluctuation in soil surface temperature, drought, soil surface being void of vegetation and unbalanced nutrient relationships) typical for cutaway peatlands during several years after peat harvesting has ceased. Additionally, the residual peat substrate in cutaways may be several thousands of years old, and thus microbe populations producing methane may have not yet been restored to the prevailing situation. On afforested croplands with continuous vegetation cover and higher soil nutrient content, the methanogenic, as well as methanotrophic populations may be larger and more vigorous than on cutaway peatlands, thus enabling higher methane consumption potential. Consequently, afforested croplands can also have a higher potential to emit CH_4 than cutaway peatlands if the soil is wet and anaerobic conditions prevail.

Annual CH_4 fluxes were compared both as median and mean values of the measured fluxes in this study. If the annual flux rate is calculated using median values some episodic events may remain underrepresented. As was seen on one site (Site 7), a few measurements of high CH_4 emissions impacted powerfully on the calculated mean annual flux rate, which was not seen in the flux rate calculated using median values.

Nitrous oxide

The mean N_2O emissions from the AC sites were similar to those reported for organic agricultural soils (Nykänen *et al*. 1995, Maljanen *et al*. 2003b, 2004, Regina *et al*. 2004), but higher to those reported from forestry drained peatlands (e.g. Martikainen *et al*. 1995, Regina *et al*. 1998, Maljanen *et al*. 2003a) in Finland. The afforested croplands had not been given any nitrogen fertilization after afforestation and the nitrogen deposition rate was low. The results suggest that even 20–30 years after afforestation, there was still a high availability of mineral nitrogen for nitrification and denitrification responsible for the N_2O emissions. The results support earlier

findings (Maljanen *et al*. 2001b) that the afforestation of cropland on peat soils does not abruptly terminate N_2O emissions.

The afforested cutaway peatlands appeared to have lower N_2O emissions than the former cropland soils. N_2O emissions from the ACP sites were slightly higher than those reported from peat extraction areas (Nykänen *et al*. 1996). This is probably a result of fertilization of ACP sites when planting trees and addition of tree litter containing organic C.

The variation between the measured sites was high. There was also a large variation in the annual emissions depending on the weather conditions. The environmental factors controlling the N_2O fluxes are complex (Groffmann *et al*. 2000) and therefore it is difficult to predict the N_2O emissions. However, according to Klemedtsson *et al*. (2005) soil C/N ratio is a possible way to scale N_2O emissions from drained organic soils. Also in our material the top soil C/N ratio was correlated with N_2O emissions.

Conclusions

Afforestation of former organic soil croplands lowers considerably the heterotrophic soil CO_2 emissions. The reduction of soil CO_2 efflux is due to the cessation of cultivation practices, which accelerate the soil decomposition processes during the active agricultural phase. Peat properties on afforested organic soil croplands differ considerably from forestry drained peatlands, resulting in slightly higher soil CO_2 emissions from afforested organic soil croplands than from forestry-drained peatlands. Mineral soil application (high ash content) had an accelerating effect on the soil CO_2 efflux on afforested organic soil croplands.

Afforestation of former peat extraction areas increases the heterotrophic soil CO_2 emissions. The reasons behind this increase are (1) fertilization and cultivation of the soil associated with afforestation, and (2) input of fresh C into the soil in the form of litter from the growing vegetation. These changes in the soil properties are likely to increase microbial activity and, consequently, heterotrophic respiration in the peat soil.

The N_2O emissions do not appear to change after afforestation of organic soil croplands. Neither do the fluxes of CH_4 change; after afforestation the areas remained small sinks of CH_4. Since CO_2 emissions from soil do appear to decrease, the afforestation of organic croplands may decrease the greenhouse impact of these lands, especially when the increased sequestration of C into the growing tree stand is taken into consideration.

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Appendix 1. Parameters of the response functions to calculate peat soil respiration rates

Study site	Sample plot	R_0	k	r^2	Study site	Sample plot	R_0	k	r^2
1	1	0.090	0.102	80.4	10	1	0.071	0.129	57.6
1	2	0.065	0.122	79.3	10	2	0.089	0.098	53.4
1	3	0.109	0.092	83.6	10	3	0.078	0.125	84.5
1	4	0.070	0.110	85.6	11	1	0.149	0.100	62.3
1	5	0.088	0.097	83.3	11	2	0.108	0.110	75.0
2	1	0.073	0.095	83.1	11	3	0.097	0.109	71.6
2	2	0.780	0.093	73.9	13	1	0.096	0.108	70.1
2	3	0.073	0.093	70.4	13	2	0.106	0.113	82.7
2	4	0.056	0.096	85.1	14	1	0.122	0.086	72.0
2	5	0.078	0.087	79.8	14	2	0.107	0.094	78.0
3	1	0.073	0.095	79.4	14	3	0.110	0.084	55.9
3	2	0.091	0.090	79.3	14	4	0.074	0.100	81.5
3	3	0.116	0.092	77.3	15	1	0.141	0.077	42.6
3	4	0.105	0.072	76.3	15	2	0.086	0.098	82.8
3	5	0.077	0.091	79.6	15	3	0.195	0.038	20.6
4	1	0.063	0.121	83.6	15	4	0.185	0.073	56.7
4	2	0.078	0.099	70.0	16	1	0.053	0.108	75.3
4	3	0.053	0.134	85.8	16	2	0.089	0.111	67.1
4	4	0.059	0.122	88.4	16	3	0.083	0.085	51.7
4	5	0.063	0.123	80.2	16	4	0.053	0.097	72.7
5	1	0.041	0.124	89.9	16	5	0.054	0.097	78.7
5	2	0.047	0.118	74.9	16	6	0.081	0.084	75.6
5	3	0.012	0.169	87.9	16	7	0.077	0.076	68.8
5	4	0.036	0.139	93.9	16	8	0.067	0.097	75.8
5	5	0.025	0.159	79.4	17	1	0.046	0.112	56.5
6	1	0.121	0.089	88.2	17	2	0.047	0.127	79.5
6	2	0.076	0.101	87.4	17	3	0.078	0.108	72.3
6	3	0.072	0.087	69.8	17	4	0.094	0.088	81.0
6	4	0.049	0.095	90.3	18	1	0.150	0.081	56.8
6	5	0.050	0.101	73.3	18	2	0.098	0.093	81.0
9	1	0.115	0.123	77.2	18	3	0.097	0.097	80.6
9	2	0.072	0.142	69.2	18	4	0.059	0.119	70.2
9	3	0.075	0.124	52.1					